Groundwater pumping and spatial externalities in agriculture[*]

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Abstract

We investigate the behavior of farmers who share an underground aquifer. In the case where seepage may occur the resource is nonexclusive, giving rise to a spatial externality whereby pumping by one user affects others nearby. Theoretically, these externalities are potentially important causes of welfare loss. Using a unique spatial data set of groundwater users in western Kansas, we are able to empirically measure the physical and behavioral effects of groundwater pumping by neighbors. To address the simultaneity of neighbors' pumping, we use the neighbors' permitted water allocation as an instrument for their pumping. We estimate that 2.5 percent of the total groundwater extracted each year in western Kansas is over-extraction due to the effects of spatial externalities. Individuals who own multiple wells internalize their own externality by trading off pumping at one well for pumping at another.

Keywords: groundwater management, spatial externalities, nonrenewable resources, common property resource

1 Introduction

Property rights to the land overlying groundwater aquifers prevent "tragedy of the commons"-type free entry and the resulting over-exploitation commonly associated with common property resources. However, the fugitive nature of groundwater may create a spatial externality whereby the holder of groundwater rights cannot fully capture the water beneath his land. Seepage, caused by hydrologic gradients and "cones of depression" from pumping, renders groundwater a partially non-exclusive resourse (Provencher and Burt, 1993). Pumping by users of the same aquifer may lower the water table, increase cost of extraction, and decrease the stock of water available for other users. This non-exclusivity dampens or eliminates an individual's incentive to forego current for future pumping, resulting in an increased rate of extraction and more rapid resource depletion (Noel, Gardner and Moore, 1980; Negri, 1989; Libecap and Wiggins, 1984).

The extent of the spatial externalities resulting from groundwater pumping from shared aquifers has been rather contentiously debated since the 1970s, when physical scientists began to note rapidly falling water tables in heavily irrigated agricultural basins. While some assert that the difference between an optimal control aquifer management solution and the competitive outcome is not large enough to justify the use of costly management measures (for example, Gisser and Sanchez, 1980; Gisser, 1983; Rubio and Casino, 2003), others maintain that the difference can be substantial, and that the over-extraction occurring in many of the world's aquifer basins is evidence of externality-induced over-exploitation (for example, Bredehoeft and Young, 1970; Burness and Brill, 2001; Koundouri, 2004; Noel, Gardner and Moore, 1980). Recently, economists have begun incorporating more realistic hydrological assumptions into their models, moving away from the "bathtub" model of an aquifer that assumes water withdrawn by one user lowers the water table instantly and uniformly throughout the entire aquifer (Saak and Peterson, 2007; Brozovic, Sunding and Zilberman, 2010). These models have imparted additional insight on the problem, particularly the spatial heterogeneity of the externality, but they generally rely on parametrized mathematical programming and simulation models to predict the effect of pumping on neighboring users. We have very little knowledge of the empirical magnitude of these externalities, whether they are large enough to affect groundwater users, or whether users respond by increasing their own pumping rates as predicted by theoretical models.

The objective of this paper is to empirically estimate the magnitude and extent of interactions, through extraction behavior, between neighboring groundwater users. The actual behavioral response may not be proportional to the response predicted from a physical-hydrological model; there is considerable uncertainty about groundwater flows, especially by farmers who may not have specialized knowledge in hydrology. Users may over-react, or they may ignore or be unaware of actual groundwater flows. For this reason, an empirical behavioral response model may be more valuable than a detailed hydrological model. In this paper, individual well-level data from irrigators in western Kansas are used to econometrically determine if the pumping of neighbors affects the groundwater extraction decision. The estimations take advantage of detailed spatial data on groundwater pumping from the portion of the High Plains Aquifer system that underlies western Kansas.

Measuring interactions between neighbors is complicated by simultaneity-induced endogeneity (individuals affect their neighbors and their neighbors simultaneously affect them) (Manski, 1993; Glaeser, Sacerdote and Scheinkman, 1996; Robalino and Pfaff, 2005; Lin, 2009); we use an instrumental variables approach to purge neighbors' decisions of this endogenous component. Groundwater users in Kansas extract water under the doctrine of prior appropriation. In Kansas this means that a permit specifying the maximum annual extraction limit, beneficial use requirements, and a date defining new permits as "junior" relative to others must be obtained from the state Division of Water Resources (Peck et al., 1988). The permit amount, while generally non-binding, is a strong determinant of actual pumping, but is uncorrelated with the pumping of neighbors whose pumping is determined by their own permit. Therefore, we use this permit amount as an instrument for neighbors' pumping. In addition, the instrument is weighted by a function of the distance between each neighbor that takes into account the way in which water moves through an aquifer. Thus, this instrumental variables approach models the spatial connectivity between users, as well as corrects for the simultaneity of neighbors' pumping decisions.

This is the first study to empirically measure economic relationships between groundwater users. We find strong evidence of spatial externalities between neighboring groundwater users that result in increased pumping. The results are further strengthened by the finding that the externality is internalized by users who own multiple wells, i.e., there is no change in behavior caused by pumping from nearby wells owned by the same user. The magnitude of the externality, however, is small. We estimate that 2.5 percent of the groundwater extracted in western Kansas is over-extraction due to the effect of spatial externalities. It is important to note that the results are highly dependent on the hydrological conditions of the aquifer under study. Areas with greater rates of hydroconductivity, different property rights regimes, or wells that are spaced more closely, for example, could be much more affected by spatial externalities. The methods presented here could be used to estimate them.

2 Background

The High Plains aquifer system underlies 174,000 square miles and portions of eight midwestern states. Ninety-nine percent of the approximately 21 million acre-feet of water withdrawn from the High Plains aquifer annually is used for irrigation. Declines in the water table have been measured since intensive irrigation became widespread in the 1970s. The largest declines (up to 150 feet) have occurred in parts of southwestern Kansas, Oklahoma, and Texas. "Aquifer sustainability" is a popular political and environmental talking point, although rather irrelevant given rates of recharge that are extremely small in most of the aquifer (excluding some regions underlying Nebraska). The aquifer was formed 2 to 6 million years ago, and should be thought of as essentially non-renewable (Miller and Appel, 1997).

While sustainability (in the sense of a steady-state rate of extraction that is equal to recharge) is unrealistic in most parts of the aquifer, public concerns about over-extraction and too-rapid resource depletion have received significant scientific attention. The early economic models of aquifer exploitation assumed open access and complete rent dissipation in the absense of regulation (Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Nieswiadomy, 1985).[1] They compared this with the opposite extreme of a single owner extracting from a single well to obtain the welfare maximizing rate of extraction (Burt, 1964). Gisser and Sanchez's (1980) findings that the welfare gains to optimal management were negligible (in the Pecos Basin of New Mexico, where their computable model was parameterized) sparked decades of research (see Koundouri, 2004, for a review). Subsequent studies explored how changes in the discount rate, increases in demand or technology adoption over time, property rights, and strategic interactions between users might affect the gains from management (Noel, Gardner and Moore, 1980; Lee, Short and Heady, 1981; Feinerman and Knapp, 1983; Gisser, 1983; Provencher and Burt, 1993, 1994; Brill and Burness, 1994; Negri, 1989; Rubio and Casino, 2003). In general, estimates of the quantitative difference between the competitive (or myopic) and the socially optimal solution remained low, from negligible to around 16 percent, resulting in little economic rationale for costly public groundwater management.

Brozovic, Sunding and Zilberman (2006) and Saak and Peterson (2007) point out that these models ignore the most basic of hydrological rules. They employ a "bathtub" model of an aquifer, which assumes instantaneous lateral flow of water. Extraction by one user lowers the water table in the next period for all other users by an equal amount, regardless of their spatial distribution. This results in a homogenous depth to groundwater for the entire aquifer and the assumption that the spatial distribution of wells does not matter (Brozovic, Sunding and Zilberman, 2010). In reality, however, water in an aquifer is contained by rock, sand, and gravel, slowing lateral movement, or hydroconductivity. A non-infinite rate of hydroconductivity both limits the spatial extent to which one user can affect another, and

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[1] Negri (1989) shows that even without free entry, rent is dissipated to λ/N, the shadow value of the stock of water divided by the number of users. Rent approaches zero as the number of landowners becomes large.

increases the potential impact of pumping on neighbors within that extent. Pumping results in a cone of depression around each well by creating a gradient between the water table in the well and the water table outside of it. The size of the cone of depression depends on many hydrological factors. The depth to water (known as head height), the distance from the aquifer bed to the water table (saturated thickness), and the speed of lateral movement (hydroconductivity or transmissivity) vary considerably even within an aquifer. When cones of depression overlap, they have a combined effect on water levels. When water extraction is seasonal, cones of depression will equilibriate over the non-pumping season to an extent governed by the hydrological characteristics of the aquifer. Pumpers can be affected by their neighbors' pumping through overlapping cones of depression within a pumping season, and by the intra-seasonal equilibriation of water levels during the non-pumping season.[2] In both cases, withdrawal by one user lowers the water table and increases the future pumping costs for neighboring users, shifting the intertemporal depletion path toward the present (Negri, 1989). Negri (1989) and Provencher and Burt (1993) identify another source of inefficiency. When property rights do not identify the precise amount of water owned by a user, water that is not withdrawn can potentially be captured by neighboring users. This undermines the incentive to store groundwater as a stock, and further shifts the extraction path toward the present (Dasgupta and Heal, 1979). Intuitively, it is in a pumper's interest to keep his water table lower than his neighbors to prevent out-flow. Such flow, however, is governed by hydrology.

Clearly, it is important to incorporate the hydrological rules governing the movement of groundwater in a model of spatial externalities, as groundwater movement is the source of the externality. Brozovic, Sunding and Zilberman (2010) found that when groundwater is modeled as a spatially explicit resource using hydrologically realistic equations of motion, the effect of the externality may be orders of magnitude larger than if estimated using a bathtub model, especially for large and unconfined aquifers like the High Plains system.

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[2] In western Kansas, the pumping season is generally from June through September, and water levels equilibriate over the winter.

Groundwater in Kansas is governed by the doctrine of prior appropriation. Prior appropriation implies “first in time, first in right”, or that junior (more recent) rightsholders may be required to cede their extraction rights to senior rightsholders in times of scarcity (Peck et al., 1988). Instead of directly applying this implication, however, the state has developed a variety of additional institutions and regulations to more clearly define the specifics of a water right. In particular, the state of Kansas administers groundwater rights through a system of permits. A potential groundwater user must apply for a permit, which if granted, specifies an annual pumping limit and the location of the field to which it must be applied. This permit has a date attached to it, defining the senioity of the right (should the doctrine of prior appropriation be employed). Through the 1970s, the period of intensive agricultural development in Kansas, groundwater pumping permits were granted to nearly anyone who requested them. Some permits are as old as 1945, but the majority (about 75 percent) were allocated between 1963 and 1981. Beginning in the 1970s, however, concern began to grow that the aquifer was over-appropriated. This led to a variety of rules designed to minimize interference between users. Kansas created five Groundwater Management Districts (GMD) that currently regulate irrigation well spacing and prohibit new water extraction within a designated radius of existing wells. Well spacing requirements are allowed to vary by extraction rate, annual extraction, characteristics of the aquifer from which it the water is drawn, and GMD.[3] For most high volume irrigation wells, minimum well spacing is around half a mile. By encouraging spatially hetergeneous well-spacing regulation for new wells, the state is acknowledging that spatial externalities in groundwater exist and potentially cause interference between neighboring users. The regulations apply only for new extraction permits, increases in annual allocation, or increases in flow rates, however, and do not affect existing wells or permits.

In addition, GMDs are allowed to designate Intensive Groundwater Use Control Areas (IGUCA), whereby special regulations can be used in areas determined to “warrant addi-

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[3] See the Rules and Regulations for individual GMDs: http://www.ksda.gov/appropriation/content/295.

tional regulation to protect the public interest". IGUCAs allow nuanced regulation to be applied to particular areas determined to have groundwater overextraction, quality, or other problems. Eight such areas have been designated since 1978; in some cases no action for existing extractors was required, and in only two were existing appropriations affected (Peck, 1995).[4] The Division of Water Resources has never ordered the strict enforcement of prior appropriation, which would shut down junior users in favor of senior rightsholders.

It is common for users to extract less than their full appropriation of groundwater. Precipitation, crop choice, and the cost of energy affect how much water an irrigator extracts in a given year. Very few users extract all of their allocation, and an average of 85 percent of users extract less than 90 percent of their total allocation per year.[5] Only about 2 percent of users extract more than their annual allocation, even though prior to 2004, there was no official penalty for over-pumping or enforcement of pumping limits.[6] Thus, there is significant room for adjustment to the effects of external factors including the pumping decisions of neighbors, especially in the time period that we consider.

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[4] Reasons that an area may be determined an IGUCA include groundwater levels declining excessively, the rate of groundwater withdrawal exceeding the rate of groundwater recharge, or an unreasonable deterioration of groundwater quality has occurred or may occur. For more information including a map of the IGUCAs, see the Kansas Department of Agriculture, http://www.ksda.gov/appropriation/content/291. In only one case (the Walnut Creek IGUCA) was there differentiation between the actions required by senior and junior rightsholders.

[5] The actual proportion of users extracting less than 90 percent of their total allocation is higher than 85%. The available data on water rights allocation is current, not historical. Thus, while we are using the extraction data from 1996 to 2005, we must use the rights information from when the data was accessed (2008). While observed pumping for a given user in, for example, 1996, may be higher than their allocation amount in the records in 2008, their allocation may have been higher in 1996. Several voluntary appropriation reduction programs were in place over the time period, and we do not have a way of knowing the exact amount of the appropriation contract in each year. We do know, however, that it could not have increased over the period, and that for the most part it is constant.

[6] Specific penalties for overextraction violations were added to the Kansas Water Appropriation Act in the fall of 2003 (KAR 5-14-10). However, enforcement only recently became common; significant resources were not directed toward enforcement until 2008. Penalties increase with the number of violations; the first offence incurs only a warning. Penalties are described on the Kansas Department of Agriculture website: http://www.ksda.gov/appropriation/cid/1554.

3 Theory and Model

While the objective of this paper is empirical, a brief, simple theoretical model is developed to generate and illustrate testable hypotheses. We compare the first order conditions generated from a social planner/single owner groundwater management problem with those obtained from an individual's extraction problem. While we do not purport that a "social planner" solution is realistically obtainable given the complexity of the groundwater basin, we expect the case where a single owner manages multiple wells in an area to approach the social planner solution. In other words, we expect spatial externalities that occur between wells to be internalized when one individual is the single owner of multiple wells.

3.1 The hydrological system

We abstract from a true hydrological model because the nature of our data only allows the estimation of spatial externalities between years, not within. Thus, we are not attempting to measure the extent of the overlap between the cones of depression caused by pumping within a season. Instead, and by necessity given annual data, we will estimate the extent and effect of the equilibriation of water levels between seasons.

The equation of motion for groundwater stock is derived from simplified hydrological mass-balance equations, and assumes that the land owned by each farmer can be thought of as a "patch" with a uniform stock of water beneath each farm. Water flows between "patches" according to hydrological rules. This is a simplification of the true physical nature of groundwater flows (Freeze and Cherry, 1979), but is appropriate given our objective of modeling groundwater flows between seasons and a notable improvement on the "bathtub" aquifer model used in previous theoretical work (Negri, 1989; Provencher and Burt, 1993). Similar assumptions have been used for the between-period movement of fish stocks (Janmaat, 2005; Sanchirico and Wilen, 2005). The equation of motion describing the change in stock over time, $\dot{s}_i$, is:

$$\dot{s}_i = -w_i + g_i(w_i) + \sum_{j \in I} \theta_{ji} s_j. \tag{1}$$

The change in groundwater stock depends on the amount agent i is pumping, w_i, and the amount of recharge to patch i, $g_i(w_i)$. Recharge is a function of return flow, and $\partial g_i / \partial w_i \geq 0$.

$\dot{s}_i$ also depends on the net flow into i's land that is caused by physical height gradients and other hydrological factors that determine how water flows within an aquifer. θ_{ij} is defined as the share of the water in the aquifer that starts in patch i and disperses to patch j by the next period, so $\sum_{j \in I} \theta_{ji} s_j$ is the net amount of water that flows into patch i from all other patches in the system. Groundwater flow is generally stock dependent; net flow is a function of the stocks of water in all the other patches, so $\theta_{ji}(s_1, s_2, ...s_I)$ and $\partial \theta_{ji} / \partial s_i \leq 0$. A simple yet hydrologically reasonable functional form assumption for net flow can be derived from Darcy's Law for water movement through a porous material and is an example of θ_{ji}: the dispersal of water between patches depends on the physical gradients between patches, $(s_j - s_i)/x_{ji}$, and the transmissivity of the material holding the water, commonly called k (Brutsaert, 2005). In this simple model, the net flow into patch i is $k_j(s_j - s_i)/x_{ji}$, where x_{ji} is the distance between plot i and j. θ_{ji} could also be more complex and consider the effects of aquifer bed topology, continuous cones of depression from pumping, or saltwater intrusion, for example (Janmaat, 2005).

In a long-run equilibrium without pumping and with a homogeneous aquifer bed, $s_i = s_j$, $\forall\, i, j$; the groundwater stocks under all land patches will be equal.

3.2 The single owner/social welfare maximizer's problem

To set the socially optimal rate of extraction benchmark, consider a single owner or social planner who must make pumping decisions for an entire aquifer basin, upon which lie many plots of land with groundwater pumps. Revenue earned on each plot i, $R_i(w_i)$, depends on how much water he extracts from the aquifer to irrigate crops, and cost C is dependent both on the amount extracted and the stock available, s_i. The smaller the stock, the greater the distance through which the water must be pumped to reach the surface, so $\partial C_i(s_i)/\partial s_i < 0$. This planner seeks to maximize the present value of aggregate profit by planning for this aquifer basin (assuming there is no flow in or out of the aquifer):

$$\max_{\{w_i(t)\}_{i=1}^{I}} \int_0^\infty e^{-rt} \left[\sum_{i=1}^{I} (R_i(w_i) - C(s_i)w_i) \right] dt, \tag{2}$$

where the planner chooses the set of pumping volumes on each plot of land in each time period, $\{w_i(t)\}$. The owner optimizes subject to the equation of motion for the water stock under each plot $\dot{s_i} = -w_i + g_i(w_i) + \sum_{j \in I} \theta_{ji} s_j$, $i = 1, ..., I$ and the transversality condition $\lim_{t \to \infty} e^{-rt} \lambda_{it} s_{it} = 0$, $i = 1, ..., I$.

In this formulation the planner is pumping water from each plot for use on that plot's crops.[7] The planner will consider each plot's shadow value of a unit of groundwater stock when determining the optimal solution, so as to internalize any externality that could occur.

The first order conditions of the current value Hamiltonian $H(w_1, ..., w_I, s_1, ..., s_I, \lambda_1, ..., \lambda_I)$ are

$$\frac{\partial R_i}{\partial w_i} = C(s_i) + \lambda_i - \lambda_i \frac{\partial g_i}{\partial w_i} \tag{3}$$

$$r\lambda_i - \dot{\lambda}_i = -w_i \frac{\partial C_i(s_i)}{\partial s_i} + \lambda_i \left(\theta_{ii} + \sum_{j \in I} \frac{\partial \theta_{ji}}{\partial s_i} s_j \right) + \sum_{\substack{j \in I \\ j \neq i}} \lambda_j \left(\theta_{ij} + \sum_{i=1}^{I} \frac{\partial \theta_{ij}}{\partial s_i} s_i \right) \tag{4}$$

The planner will choose the crop-water combination such that the value marginal product of the water is equal to the marginal pumping cost plus the shadow value of water. The shadow value is a function of the flow onto and off of the farmer's plot. The social optimum is a function of the water stock on all the parcels of land under the owner's control, all of the interconnections between parcels, and all of the shadow values. It is possible, given

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[7] This is in contrast to the single owner/social planner depicted in Negri (1989) where the planner controls the entire swath of land, pumps from only one location, and then presumably distributes it to the spatial location where it is needed.

heterogeneous costs or revenue across plots i, that interior solutions will not be optimal for all plots (i.e., optimal pumping may be zero in some plots).

This program is identical to the single owner/social planner problem normally analyzed using a bathtub aquifer model if we assume that transmissivity is infinite, the aquifer is parallel sided and flat bottomed, return flow is zero, and parcels are perfectly homogeneous (Negri, 1989). It does not matter where the wells are located or how many there are, as long as water can be transported costlessly to the entire surface of the parcel. If we make these assumptions, the first order condition 4 can be summed over all the parcels and collapses to $\dot{\lambda} = r\lambda + Nw\frac{\partial C(s)}{\partial s}$, where N is the total number of parcels the planner controls, and w is the total amount of water withdrawn per parcel. By integrating, using the transversality condition, and combining the first order conditions, the marginal condition for an arbitrary $\bar{t}$ is obtained:

$$\frac{\partial R}{\partial w} = C(s) + N \int_{t}^{\infty} e^{-r(t-\bar{t})} w \frac{\partial C(s)}{\partial s} dt. \tag{5}$$

To be intertemporally efficient, a landowner will extract water until the marginal value product of water is equal to the marginal cost of extraction plus the value of the marginal unit of water as stock, which is the definition of the shadow price λ. The marginal unit left as stock has value because it reduces future pumping costs. This is the standard Hotelling solution, where the shadow value grows as a function of the rate of interest (Hotelling, 1931).

3.3 Individual, dynamically optimizing farmer

Now compare the social planner's solution to the solution of a group of individual landowners, each having property rights to one "patch", that partially share the water resource. The objective function faced by one of these farmers is:

$$\max_{\mathbf{w}_i(t)} \int_{0}^{\infty} e^{-rt} \left[R_i(w_i) - C(s_i) w_i \right] dt, \tag{6}$$

with the equation of motion as in equation 1 and transversality condition $\lim_{t \to \infty} \lambda_{it} s_{it} = 0$. This problem is similar to that that posed in Janmaat (2005), but dissimilar to much of the previous literature on spatial fisheries, in that each parcel is owned by an individual with no claim on the profit earned in any other parcel.

The first order conditions derived from the maximization of the Hamiltonian can be combined and then integrated to obtain the marginal condition for an arbitrary $\bar{t}$:

$$\frac{\partial R_i}{\partial w_i} = C(s_i) + \left(1 - \frac{\partial g_i}{\partial w_i}\right) \int_t^{\infty} e^{-\left(r - \theta_{ii} - \sum_{j \in I} \frac{\partial \theta_{ji}}{\partial s_i} s_j\right)(t - \bar{t})} w_i \frac{\partial C_i(s_i)}{\partial s_i} dt. \tag{7}$$

The necessary condition for intertemporal optimization shows that water is extracted until marginal profits are equal to marginal extraction costs plus the present value of the shadow value of water. A unit of groundwater left in the aquifer has value only in proportion to the amount that the owner can capture in the future. Stock dependent net flow implies $\sum_{j \in I} \partial \theta_{ji} / \partial s_i < 0$, and the $\sum_{j \in I} \partial \theta_{ji} / \partial s_i$ term captures the extent to which the resource is common. As this term gets larger, less of the water left as stock can be captured by the owner of the land, effectively increasing the discount rate and decreasing the value of the marginal unit of stock. This shifts the extraction path towards the present.

Higher values of $\partial g_i / \partial w_i$, the function describing recharge and return flow decrease the value of the marginal unit of groundwater as stock and increase present period pumping.

Empirically, we expect the effect of neighbors' pumping to be positive regardless of the sign of the gradient, i.e., regardless of whether i's stock of water is greater than j's, or vice versa. Consider the ways in which stock of water affects the user's optimization problem. First, it affects their marginal cost of extraction. Second, it affects the flow into and out of a user's plot. In part (a) of figure 1, individual i faces a larger stock, or equivalently a shorter depth to the water table than does j. Due to the negative gravitational gradient, water will flow out of i's plot, decreasing i's shadow value of water. To capture the water before it can flow out and extract it at a lower marginal cost, i would increase pumping.

In part (b) of figure 1, the gravitational gradient is positive, causing water from j to flow to i. This reduces the effect of current period pumping on future pumping by decreasing i's future marginal cost of extraction. Thus, current period pumping would increase. The linkage between users causes each individual to marginally increase pumping, regardless of who is "uphill" from whom. Anything that increases the linkage between patches will also increase present period pumping, including a greater hydroconductivity, a smaller distance between wells, and higher pumping by neighboring patch owners.

Finally, the solution to the individual's dynamic optimization problem leads to greater extraction than would occur under a single owner, as long as $\theta_{ii} \neq 1$. θ_{ii} describes the proportion of water starting in patch i that stays in patch i the following period. If all of the water that starts in i stays in i, for all i, then there is no lateral flow in the aquifer and the derivatives $\partial\theta_{ji}/\partial s_i$ and $\partial\theta_{ij}/\partial s_i$ are zero. Consider first order conditions 4 and 7. In 7, the interest rate is decreased by the sum of the net flow derivatives $\sum\limits_{j\in I} s_j(\partial\theta_{ji}/\partial s_i)$, and with stock dependent flow, this sum is negative, effectively increasing the interest rate. In the central planner's first order condition 4, the interest rate is further adjusted by the derivatives of flow going from i to j. Given stock dependent flow, $\partial\theta_{ij}/\partial s_i \geq 0$; an increase in the stock level at i will cause more movement out of patch i to other patches. Thus, as long as $\sum\limits_{\substack{j\in I\\ j\neq i}} \partial\theta_{ij}/\partial s_i > 0$, it will negate the effect of $\sum\limits_{j\in I} \partial\theta_{ji}/\partial s_i$ and the total amount of water withdrawn per period by the social planner will be less than the total amount of water withdrawn by all of the individuals.

This model leads to several testable hypotheses. First, we empirically estimate the equation of motion. We measure the effect that a farmer has on his own depth to groundwater at his own well. We also measure the effect that pumping by a farmer's neighbors has on the depth to groundwater at his own well. For purely physical reasons, we expect own pumping to have a greater effect on the depth to groundwater than pumping by neighbors has. Second, we test if pumping by a farmer's neighbors has an effect on the pumping behavior of that farmer. The theoretical model shows that extraction by neighbors should increase pumping. Finally, by comparing the first order conditions of the individual's optimization problem with those of the social planners, we hypothesize that if a farmer owns multiple wells in adjoining parcels, he will manage them differently than if each well were owned by a different person. Specifically, we can test if any effect of pumping from his own wells (on water table height or pumping) is less than the effect of pumping from wells owned by others.

4 Empirical analysis

4.1 Data

A unique data set allows the empirical exploration of these hypotheses. Kansas has required the reporting of groundwater pumping by water rights holders since the 1940s, although data from 1996 to the present are considered to be complete and reliable. The data are available from the Water Information Management and Analysis System (WIMAS).[8] Included are spatially referenced pumping data at the source (well or pump) level, and each data point has the farmer, field, irrigation technology, amount pumped, and crops grown identified. A sample of the data is used for the analysis that includes only one well per water rights owner.[9] There are about 6,000 sampled points of diversion for each of the 10 years from 1996 to 2005. These are combined with spatial datasets of recharge, water bodies, and other geographic information.

The United States Geological Survey's High Plains Water-Level Monitoring Study maintains a network of nearly 10,000 monitoring wells. Data from these wells have been used to estimate yearly water levels. The USGS also provides spatial data on specific yield and

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[8] http://hercules.kgs.ku.edu/geohydro/wimas/

[9] The dataset includes information on all groundwater wells in Kansas. We use only one well per water rights owner for the analysis because when we construct the spatial neighborhoods (described in the last paragraph in this section), we want to differentiate between wells owned by others and wells owned by the same person. The tools available in ArcGIS do not allow us to identify the water rights owner when constructing the spatial neighborhoods, and because of the size of the dataset, it would be impossible to do by hand. Therefore, we include only one well per owner in the analyzed dataset, but add up his other wells and amount pumped to use as an explanatory variable.

transmissivity of the aquifer, and rainfall data are obtained from the PRISM Group at Oregon State University.[10] Relevant information from the geographic files was captured at the points of diversion (well) level using ArcGIS.

Summary statistics for the variables used in the analysis are presented in tables 1 and 2. An average of 144 acre-feet of water are extracted per irrigation well per year. Many irrigators own multiple wells, and pump an average of 1200 acre-feet in total. Each well irrigates an average of 137 acres, and each well owner irrigates an average of 943 acres. The average depth to groundwater is 114 feet, but ranges from 0.8 to over 350 feet. The average change in the depth to groundwater from one year to the next is one foot. Over the ten year period, each point of diversion got an average of 22 inches of precipitation per year. Recharge, hydroconductivity, and soil characteristics are time-invariant and are estimated by the United States Geological Survey and evaluated at each point of diversion. Recharge to the Kansas portion of the High Plains Aquifer is low; average recharge is 1.4 inches. The mean hydroconductivity is 65.8 feet per day.

Three measures of soil quality are used in the analysis. Irrigated capability class is a categorical variable describing the suitability of the soil for irrigated crops; the first category being the most suitable. 45% of the plots have soils in category 1, and we use an indicator variable equal to one if the soil is in category 1, and zero otherwise. The average available water capacity is 0.18 cm/cm, and the mean slope (as a percent of distance) is 1.1%.

A variety of spatial neighborhood variables are constructed to investigate the effect of neighbors' pumping. Summary statistics are provided in table 2. A half mile, one, two, three, and four mile radius around each well is constructed and the average number of neighboring wells, and the number of acre-feet of groundwater extracted from those neighboring wells is included in the table of summary statistics. Weighted gradients, calculated as the difference in water table height between two wells, divided by the distance and multiplied by hydroconductivity, are used to weight the amount of water pumped by neighbors by the

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[10] PRISM (Parameter-elevation Regressions on Independent Slopes Model) data sets are recognized worldwide as the highest-quality spatial climate data sets currently available. http://www.prism.oregonstate.edu/

impact they should have. To obtain average marginal effects, the estimated coefficient must be multiplied by the average weight; we provide the average weights in table 2.

4.2 Empirical Estimation Strategy

4.2.1 Estimation of the equation of motion

Using the data from Kansas, we can directly estimate the equation of motion and test the effect of pumping on the change in groundwater stock from one year to the next. The stock of groundwater can be equivalently measured as lift height, or the distance from the ground surface to the top of the water table. Because our data contain information on static levels (the top of the groundwater table measured in winter, presumably after equilibrating from the pumping season), we use this as a measure of stock. Given the assumptions of the equation of motion, the change in the depth to groundwater should depend on the amount that is pumped at the location where the depth is measured (own pumping), the amount pumped by neighbors, the distance between the farms, the relative heights of the water tables, and the transmissivity of the aquifer at that location. Models of the form

$$h_{it+1} - h_{it} = \beta_0 + \beta_1 w_{it} + \beta_2 w_{jt} + \mathbf{X}'_{it}\beta_3 + \varepsilon_i. \tag{8}$$

are estimated, where $h_{it+1} - h_{it}$ is the change in the depth to groundwater from one year to the next, w_{it} is own-well pumping, w_{jt} is pumping by neighbors within a specified radius, and $\mathbf{X}$ is a vector of hydrological characteristics and interaction terms. Equation 8 estimates this physical relationship between water pumped at various locations and changes in groundwater depths.

4.2.2 Identification strategy for the endogenous behavioral relationship

To investigate the behavioral and economic relationship between neighboring groundwater users, a reduced form approach is used. We would like to estimate

$$w_{it} = \mathbf{X}'_{it}\beta + \eta w_{jt} + \varepsilon_{it}, \tag{9}$$

the effect of a neighbor's pumping, w_{jt}, on water extraction by an individual, w_{it}. However, the estimation of neighbors' interactions, η, is problematic because of the simultaneity-induced endogeneity bias resulting from each observation being each other observation's neighbor so $cov(w_{jt}, \varepsilon_{it}) \neq 0$. An identifying assumption is needed to remove the bias, which is likely to be positive if, as we posit in this paper, there is a strategic interaction between neighboring groundwater users that leads to overpumping relative to the dynamic optimum. One method that has been used to to identify the effect of the behavior of neighbors on an individuals' land use choices is to use the physical attributes of neighboring parcels as instruments for that neighbor's choices (Irwin and Bockstael, 2002; Robalino and Pfaff, 2005). We use a similar strategy, but in addition to using the physical attributes of neighboring parcels, which are rather homogeneous in this region, we make use of the fact that in Kansas each groundwater user has an extraction permit that specifies the maximum annual extraction (Peck, 1995). The permitted amount is expected to strongly determine the quantity pumped by an individual permit owner, but be uncorrelated with the pumping decision of the individual's neighbors. Neighbors' pumping decisions are determined by their own permitted amounts. Let a neighbor's permit amount be c_j; if $cov(w_{jt}, c_j) \neq 0$ (neighbors' pumping is significantly correlated with their own permit amount, the first stage in the instrumental variables regression), but $cov(\varepsilon_{it}, c_j) = 0$ (neighbors' permit amounts are uncorrelated with individual i's pumping decision, a valid exclusion restriction), then neighbors' permit amounts can be used as an instrumental variable for neighbors' pumping.

We are also interested in investigating the relationship between multiple wells owned by the same individual. Theoretically, an individual that owns multiple wells in close proximity with one another would internalize any spatial externality that occurs between them; the elevated pumping levels predicted by the model in response to pumping by neighbors would not occur if those neighboring wells were owned by the same user. By contrasting the estimated effect of pumping at neighboring wells owned by others with the effect of pumping at neighboring wells owned by the same individual, we can measure the effect that is explicitly due to the pumping of others. Because permits are defined at the well level, the same method of using the permitted quantity at other wells (here, those owned by the same individual) as an instrument for actual pumping at those wells can be used.

The specification of equation 9 has additional complications that must be addressed before estimation. First, each individual has many neighbors. We are interested in the cumulative effect of pumping by all neighbors on an individual's extraction decision. We are also interested in the estimation of the (hypothesized) decreasing effect of neighbors' pumping as the distance separating them increases. We construct a series of concentric buffers around well i, beyond the largest of which interaction is not expected to occur. Extraction in the larger buffers is measured exclusively of extraction in the smaller ones. We then sum the pumping of all neighbors within that buffer. We expect interaction to be the largest at close distances and the effect to approach zero at the distance increases. Because pumping at the larger buffers is exclusing of the inner ones, the full effect of pumping in the neighborhood is the sum of the effect in all the buffers.

There is a functional relationship between the distance between wells and the expected effect of pumping by j on pumping by i, creating spatial dependence (Anselin, 1953). For example, we expect the relationship between pumping by i and j to be larger if i and j are closer together. Fortunately, we know the nature of the spatial dependence; it is defined by Darcy's Law, an equation describing the physical movement of a liquid through a porus material, that is in this case, is water in an aquifer. We weight the (instrumented) effect of neighbors' pumping by $k_j \cdot \frac{h_{it}-h_{jt}}{x_{ji}}$, where $h_{it} - h_{jt}$ is the difference in lift height in a given time period, k_j is hydroconductivity, and x_{ji} is the distance between i and j. These weights adjust the amount pumped by the effect that it should have. Own pumping at other wells is similarly weighted.

Thus, a series of simultaneous equations explain farmers' behavior, and can be modeled with a two-step estimation procedure. First, neighbors' pumping is predicted as a function of the permitted amount of pumping at that well, an exogenous well characteristic. Let $i = 1, ..., N$ index all the wells in the groundwater basin. For each individual well i, a neighborhood M is defined. M could potentially include all water users in the aquifer (N). Let $j = 1, ..., M$ index wells in the spatial neighborhood owned by others, and $s = 1, ...M$ index wells in the neighborhood owned by the same individual as well i. Then the equation

$$w_{jt} \quad = \quad \mathbf{X}'_{jt}\beta + \alpha c_j + \varepsilon_{jt}, \forall\, j = 1, ...M \tag{10}$$

is the first stage regression for neighbors' pumping, where X_{jt} is a matrix of individual-well specific physical characteristics, including precipitation and soil quality, and c_j is a neighbor's extraction permit amount.

A similar first stage regression is used for pumping from wells that are owned by the same individual as well i:

$$w_{st} = \mathbf{X}'_{st}\beta + \alpha c_s + \varepsilon_{st}, \forall\, s = 1, ...M. \tag{11}$$

Here, w_{st} is "own" pumping at other wells, and c_s is the quantity permitted for extraction at those wells. Table 6 presents the results of the first stage regression. The extraction permit amount is a statistically significant predictor of the amount pumped by an individual.

In the second stage, predicted levels of pumping from equations 10, $w_{jt}*$, and 11, $w_{st}*$, are used to estimate the expected pumping at i using two stage least squares:

$$w_{it} = \mathbf{X}'_{it}\beta + \alpha c_i + \gamma \sum_{\substack{s=1 \\ s\neq i}}^{M} \left(k_s \cdot \frac{h_{it} - h_{st}}{x_{si}} \right) \cdot w^*_{st} + \eta \sum_{\substack{j=1 \\ j\neq i}}^{M} \left(k_j \cdot \frac{h_{it} - h_{jt}}{x_{ji}} \right) \cdot w^*_{jt} + \mu_{it};\ M \subset N. \tag{12}$$

X_{it} is a matrix of individual-well specific regressors that affect the pumping decision including the number of acres irrigated, rainfall, and soil quality indicators. The weights $k_j \cdot (h_{it} - h_{jt})/x_{ji}$ come from the equation for Darcy's Law describing the movement of a fluid through porous material.[11] Again, $h_{it} - h_{jt}$ is the difference in lift height in a given time period, k_j is hydroconductivity, and x_{ji} is the distance between i and j. These weights adjust the amount pumped by the effect that it should have. For example, if the distance between two wells is greater, the effect should be smaller. If the height gradient is larger, the effect should be greater. c_i is well i's permitted allocation of groundwater, and the estimated coefficient η measures the effect of the spatial externality. γ measures the effect of own pumping at others wells owned by the same individual.

4.3 Results and Discussion

Table 3 shows the results from the estimation of equation 8, the basic physical relationship between acre-feet that are pumped from one's own well and surrounding wells and the change in groundwater lift height. From table 3, regressions 1 through 5, one hundred acre-feet pumped in one year are associated with an increase in lift height of 0.30 to 0.48 feet at that same well the following year, depending on the model specification. Average pumping at a single well is 144 acre-feet, and the observed average change in lift height is 1.0 feet, so these estimates are quite reasonable.

Also included is the sum of the acre-feet pumped in increasing distances around i. As expected, the effect is significantly smaller than the effect of own-well pumping, and the effect of neighbor's pumping decreases as the distance from i increases. One thousand acre-feet of pumping within a half mile causes an increase in lift height of about 1.5 feet, while one thousand acre-feet pumped 1-2 miles away is associated with an increase in lift height of 0.9 feet. Figure 2 illustrates the decreasing effect; the effect disappears when the distance increases to 3 and 4 miles.[12]

In column 6 of table 3, measures of hydroconductivity are included. Hydroconductivity

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[11] For the estimation, we use the depth to groundwater (h) as a measure of stock, instead of actual stock (the state variable used in the theoretical section). Thus, $\theta_{ji}(h_1, h_2, ...h_I) = -\ \theta_{ji}(s_1, s_2, ...s_I)$.

[12] A lag of neighbors' pumping was included in these regressions; (Brozovic, Sunding and Zilberman, 2002) argue that it can take a significant amount of time for the effect of pumping in one location to be transmitted to another location. However, for these locations and hydrological conditions the lags were insignificant, so were excluded from the final model.

is a measure of how well water flows laterally through an aquifer. Higher levels of hydroconductivity, when interacted with neighbor's pumping, may be associated with a greater increase in lift height. However, higher hydroconductivity may also result in more flow through the aquifer in general, and higher recovery from pumping. The results from the regression appear to support the second hypothesis. The hydroconductivity variable is significant and negative and the interaction term is insignificant, indicating that in areas with higher hydroconductivity, the depth to the water table increases less from year to year, all else constant.

Recharge measures the potential for percolation into the aquifer; precipitation measures the amount of water (in addition to own pumping and subsequent application as irrigation) that is available to recharge the aquifer. Both variables are expected to decrease the depth to groundwater, although recharge to the aquifer in most parts of the aquifer is very small. The estimated marginal effect of precipitation is negative and the estimated effect of recharge is negative for slightly above average levels of precipitation, both as expected.

We expect multiple wells owned by the same person to be managed differently than multiple wells owned by different people. Just as the optimal extraction rate of a social planner would be lower than that of a group of individuals, the extraction rate of an individual who owns several wells would be lower than if different people owned each well because any externalities occuring between wells would be internalized. One way to test this hypothesis is to determine if pumping from other wells owned by the same person has an effect on the depth to groundwater at location i. It is expected that a farmer would manage his wells such that the overall level of groundwater beneath his land decreases at whatever he has determined the optimal extraction path to be. He is more likely to substitute pumping from one well with pumping from another. Thus, we expect pumping from other wells owned by the same person as the well at location i to have a smaller effect than pumping from wells owned by neighbors on the depth to groundwater level at i. The estimates presented in table 3 confirm this result. The number of acre-feet pumped from wells owned by the same person has an estimated effect that is smaller in magnitude. An equal amount of groundwater pumped from other wells owned by i has less than $1/5$ the effect of extraction at wells owned by others in a 1-mile radius. While the relationship contains behavioral implications which have not yet been explicitly estimated, it is evidence that a single owner manages his wells differently than would multiple owners; this was predicted in the theoretical model.

We note that while the parameter estimates are statistically significant, the R^2s of the regressions are low. Hydrological variation and other factors are likely to cause variation in groundwater depth that we don't have the ability to measure. In addition, while the estimated effects of neighbors' pumping is small, and may not even be economically important in the short term (unfortunately, we do not have the data to estimate a pumping cost function), it can still be the source of a strategic externality. While a pumping cost externality may certainly be important, Negri (1989) and Dasgupta and Heal (1979) show that potential capture by neighboring users undermines the incentive to store groundwater as a stock. Moreover, only the perception of a physical movement of water is necessary for a strategic effect to occur. In reality, typical groundwater users are unaware of exactly how their neighbors affect them hydrologically. However, the existence of minimum well spacing requirements, limits on pumping rates, and recognized conflicts between users justifies the perception of movement of water that users may respond to. Users may over- or under-react, and for this reason, an empirical behavioral response model may be more valuable than a detailed hydrological model to measure interactions between users.

Given that there is empirical evidence for significant lateral flow of water corresponding to the equation of motion, we expect groundwater users might adjust their behavior in response to the pumping of neighbors. The reduced-form behavioral model is estimated using equations 10 and 12, and the results are presented in tables 4 through 6. Table 6 reports the results of the first stage relationship, and shows that the F-statistics for the IV are very high. Table 4 shows the results of the estimation of equation 12, first without the weights on neighbors' pumping (row 1), and second without the instruments (row 3). These regressions provide an upper bound of the effects of neighbors' pumping on own pumping, as they do not correct for spatial gradients or the simultaneity of neighbors' actions. Table 6 is a test of the instruments, and shows that neighbors' pumping is highly correlated with the neighbors' pumping permits.

The regressions in tables 5 are estimated with a simultaneous system of equations, using neighbors' appropriation contracts as instruments for neighbors' pumping. Controlling for authorized quantity, precipitation, and soil and hydrological characteristics, we find that the weighted sum of neighbors' pumping has a significant effect on the quantity of water extracted. The average effect (presented at the bottom of the tables), which is the coefficient on neighbors' pumping multiplied by the average weight (provided in table 2), clearly decreases as the neighborhood gets larger (farther from i). Column 1 of table 5 uses the weighted sum of the neighbors within 0.5 miles, column 2 all neighbors within 0.5 to 1 mile, column 3 all neighbors within 1 to 2 miles, column 4 all neighbors within 2 to 3 miles, and column 5 all neighbors within 3 to 4 miles. The average effect shows that, for example, 1000 acre-feet of additional pumping by neighbors within a half mile radius, at the margin and with the average gradient weight, would cause one to increase their own pumping by about 12 acre-feet. One thousand acre-feet of pumping by ones' neighbors within a one mile radius is associated with an increase in pumping of a similar amount. Figure 3 shows that at two miles the effect decreases dramatically, nearing zero. The estimates are significant at the 0.1% level.

Table 4 compares the effects of neighbors' pumping using several specifications of the independent variable. The estimated effects using the instruments (row 5) are about half the magnitude of the estimated effects reported in row 3 that are estimated without the instruments. This is what we would expect; rather than measuring the effect that i and j simultaneously have on each other, we can isolate the effect of j on i with the instrumental variable approach. Row 2 shows that if we treat all neighbors the same and do not correct for their distance, hydroconductivity, and height gradient, we greatly overestimate the effect of neighbors' pumping.

Using the summary statistics presented in table 2, the average amount of water pumped by neighbors in a one mile radius is 239 acre-feet (47 acre-feet are within 0.5 miles). Therefore, for the average groundwater extractor, pumping by all neighbors within one mile would cause him to increase his own pumping by an average of 3.6 acre-feet. Average pumping is 136 acre-feet, so the spatial externality effect of neighbors' pumping accounts for about 2.5 percent of total pumping.

Finally, we contrast the behavioral response to extraction by nearby neighbors to extraction from nearby wells that the owner himself controls. We use the same procedure to instrument for own pumping at other wells using the appropriation contract at those wells as an instrument to correct for simultaneity, and weight by the the hydroconductivity-height-distance gradient. The average "own" effect (the effect on pumping at i of pumping at other wells owned by the same person) is presented at the bottom of table 5. The average own effect is much smaller in magnitude than the effect of pumping by neighbors. These results indicate that when a farmer controls multiple wells in the same area, he will internalize the spatial externality caused by pumping at his own nearby wells. He can do this by trading off pumping at one well with pumping from another, and on average farmers seem to do so in a way that causes a smaller decrease in the water table level from one year to the next.

5 Conclusion

The inefficiencies resulting from the exploitation of common property resources are of continuing concern to economists, resource managers, and policymakers. In the case of groundwater or other resources where property rights exist, but may be incomplete because spatial movement of the resource makes it impossible to fully capture what is technically owned, the measurement of this spatial movement is important because it quantifies the resulting inefficiency. The externalities resulting from groundwater pumping from a common aquifer have been extensively discussed and their importance debated (Dasgupta and Heal, 1979; Gisser and Sanchez, 1980; Eswaran and Lewis, 1984; Negri, 1989; Provencher and Burt, 1993; Rubio and Casino, 2003; Msangi, 2004; Brozovic, Sunding and Zilberman, 2006; Saak and Peterson, 2007), but this paper is the first to measure them empirically.

We find evidence of both a physical movement of groundwater between farms and a behavioral response to this movement in the agricultural region of western Kansas overlying the High Plains Aquifer, although the estimates of both are small in magnitude. The movement of water in the aquifer is in response to physical height gradients caused by groundwater extraction, as well as other hydrological properties that affect groundwater flow. We find that 100 acre-feet of pumping is sufficient to lower the static level of the water table at one's own well by 0.31 to 0.48 feet, and 1000 acre-feet of pumping by neighbors within about a two-mile radius can reduce the static level at one's well by 0.8 to 1.5 feet the following year. At the average levels of pumping by an individual and his neighbors, this amounts to a reduction in the water table of 0.64 to 1.02 feet per year, about 0.8 percent of the mean depth to groundwater.[13] This is unlikely to be economically significant in any given year, but may be over the life of a well.

In theoretical models, the behavioral response resulting from the inability to completely capture the groundwater to which property rights are assigned causes some degree of over-extraction. Using an instrumental variable and spatial weight matrices to overcome estimation difficulties resulting from simultaneity, we find that on average, the physical connectivity and behavioral feedback effects that cause the spatial externality result in over-extraction that accounts for about 2.5 percent of total pumping. Kansas farmers would apply 2.5 percent less water in the absense of spatial externalities (if, as an unrealistic example, each farmer had an unpenatrable tank of water that held his or her portion of the aquifer).

Strengthening the evidence of the behavioral response to the spatial externalities caused

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[13] Using the estimates of 0.21 to 0.49 feet/100 acre-feet of own pumping, 1.5 feet/1000 acre-feet of neighbors' pumping within a one mile radius, average own pumping of 136 acre-feet, average one mile radius pumping of 239 acre-feet, and average depth to groundwater of 114 feet.

by the movement of groundwater is the empirical result that when a farmer owns multiple wells, he does not respond to pumping at his own wells in the same manner as he responds to pumping at neighboring wells owned by others. In fact, the response to pumping at his own wells is to marginally decrease pumping, thus trading off the decrease in water levels between spatial areas and internalizing the externality that exists between his own wells.

Policy options to reduce the inefficiency caused by the spatial movement of water in the aquifer are relatively limited because the inefficiency is caused by physical movement. Libecap and Wiggins (1984) argue that unitization and contracting between neighbors should occur naturally; landowners most affected by pumping from their neighbors would buy up neighboring land to reduce the movement out of their land. Our results indicate that this would be effective; water pumped from wells owned by the same person does not have the same effect as an equal amount of water pumped by neighboring landowners due to management by the landowner (the internalization of the externality). Moreover, the externalities are concentrated in space; the effect of neighbors' pumping decreases to nearly zero at distances of three to four miles.

These results also suggest that the minimum spacing requirements for new wells are necessary, but they may not be sufficiently large to entirely prevent interaction. While current regulations vary by groundwater management district and the size of the well and level of extraction, minimum spacing requirements are rarely larger than one-half mile. Our results show that irrigation pumping affects other wells between seasons at distances of up to one mile. Additionally, the regulations do not have any effect on the nearly 20,000 existing wells with active extraction permits. Given the small number of new extraction permits approved each year, distance-weighted reductions in the annual pumping limit for wells that are within one mile of each other would be more effective in reducing the effect of spatial externalities, especially in areas where irrigation wells are dense and the effects of neighbors pumping is higher than average. However, the costs of such a regulation should be compared to the benefits, as we find that spatial externalities account for a very small proportion of total extraction.

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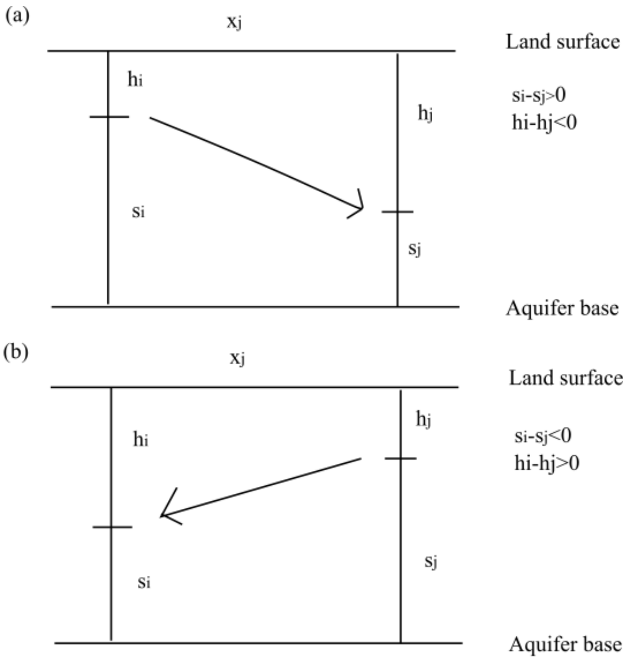

Figure 1: Relationship between owners i and j in terms of depth to groundwater

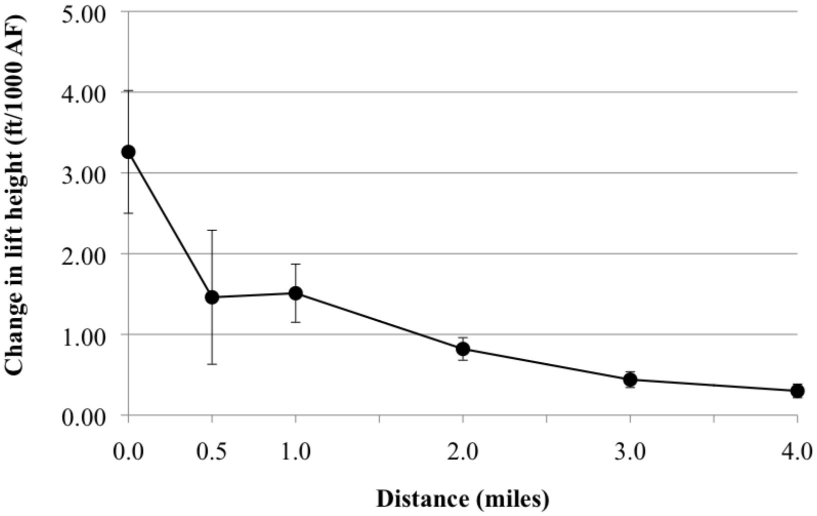

Figure 2: Effects of neighborhood pumping on the change in water table height

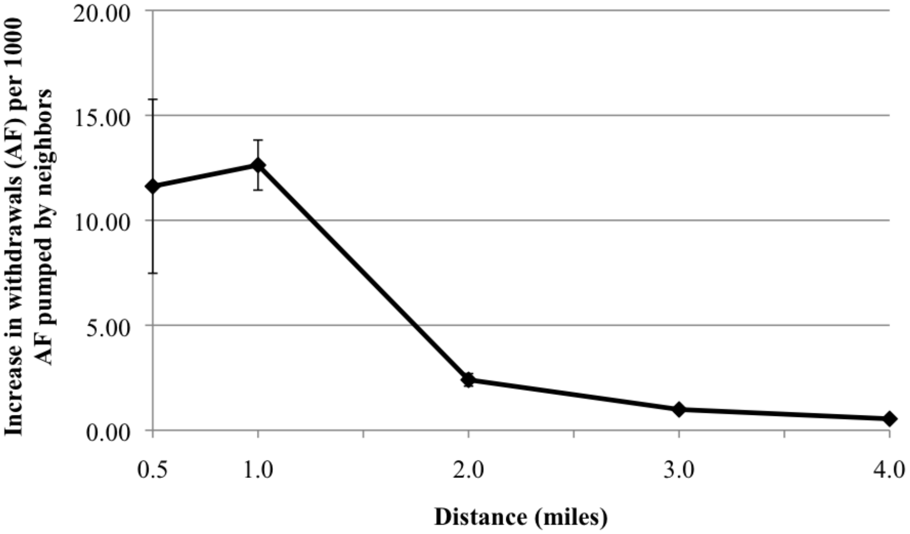

Figure 3: Effects of neighborhood pumping on the groundwater withdrawals, evaluated at average gradient weight

Table 1: Summary Statistics, 1996-2005

Individual-year level variables	N	Mean	Std. Dev.
Acre-feet pumped, single well	58531	144.4	120.1
Acre-feet pumped, single water rights owner	58531	1217.4	4212.1
Acres planted on irrigable land, single well	58531	137.3	84.7
Acres planted on irrigable land, single water rights owner	58531	943.1	2653.5
Depth to groundwater (ft)	58531	114.3	76.1
Change in depth to groundwater (ft)	58531	1.2	14.6
Change in depth to groundwater, county average (ft)	459	1.0	8.2
Precipitation (in)	58531	22.3	5.8
Individual level variables			
Recharge (in)	6312	1.4	1.3
Hydroconductivity (ft/day)	6312	65.8	75.2
Slope (% of distance)	6312	1.1	0.9
Irrigated Capability Class	6312	0.5	0.5
Available water capacity (cm/cm)	6312	0.2	0.03
Distance to nearest neighbor (mi)	6312	0.7	0.5

Table 2: Summary Statistics of Spatial Neighborhood Variables

	Number of neighboring wells	Acre-feet pumped	Average gradient weight
0.5 mile radius	0.06	46.70	75.45
	(0.24)	(103.75)	(148.09)
1 mile radius	0.49	239.12	46.80
	(0.78)	(274.26)	(85.43)
2 mile radius	3.44	977.05	24.03
	(2.54)	(805.35)	(43.97)
3 mile radius	9.61	2118.09	15.89
	(5.72)	(1611.79)	(28.91)
4 mile radius	17.51	3520.91	14.37
	(9.16)	(2510.62)	(25.78)

Note: Standard deviations in parentheses.

Table 4: Summary of Effects of Neighbors' Pumping With Different Specifications of Independent Variable

Year	0.5-mile	1-mile	2-mile	3-mile	4-mile
(1) Neighbors' pumping (unweighted, no IV)	0.0619	0.0553	0.0306	0.0228	0.0193
(2) Neighbors' pumping (weighted†, no IV)	0.0004	0.0004	0.0003	0.0002	0.0002
(3) Average effect‡ (weighted, no IV)	0.0287	0.0178	0.0065	0.0033	0.0027
(4) Neighbors' pumping (weighted, with IV††)	0.00015	0.00025	8.63e-05	4.90e-05	3.09e-05
(5) Average effect (weighted, with IV)	0.0116	0.0126	0.0024	0.0010	0.0005

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. N is 59800. †Neighbors' pumping is a weighted sum, absolute value of the weights. ‡Average effect=beta on neighbors' pumping*average weight. ††Estimated coefficient is from the results of the regressions using the instrumental variables, reported in table 5.

Table 3: Estimation of the Equation of Motion (Dependent variable: Change in the depth to groundwater from one year to the next (ft))

	(1) 0.5-mile	(2) 1-mile	(3) 2-mile	(4) 3-mile	(5) 4-mile	(6) Concentric buffers	(7) 1-mile
Amount pumped at i	0.00481	0.00414	0.00311	0.00313	0.00296	0.00211	0.00401
	(0.0007)***	(0.0007)***	(0.0007)***	(0.0007)***	(0.0007)***	(0.0008)**	(0.0007)***
Amount pumped at other wells owned by i's owner	0.00028	0.00028	0.00027	0.00025	0.00024	0.00026	0.00027
	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*
Neighbors' pumping, 0.5 mi	0.00146						
	(0.0008)						
Neighbors' pumping, 1 mi		0.00163				0.00071	0.00135
		(0.0003)***				(0.0003)*	(0.0004)***
Neighbors' pumping, 2 mi			0.00093			0.00051	
			(0.0001)***			(0.0002)**	
Neighbors' pumping, 3 mi				0.00059		0.00015	
				(0.0001)***		(0.0001)	
Neighbors' pumping, 4 mi					0.00052	0.00026	
					(0.0001)***	(0.0001)**	
Precipitation (in)	-0.21190	-0.20864	-0.20537	-0.20642	-0.20533	-0.20079	-0.22978
	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***	(0.0232)***
Potential recharge (in)	1.95678	1.85376	1.68370	1.67688	1.64140	1.50967	1.44528
	(0.3678)***	(0.3685)***	(0.3699)***	(0.3705)***	(0.3712)***	(0.3720)***	(0.3746)***
Precipitation*recharge	-0.03830	-0.03558	-0.03084	-0.03044	-0.02924	-0.02598	-0.02312
	(0.0117)**	(0.0117)**	(0.0118)**	(0.0118)**	(0.0118)*	(0.0118)*	(0.0119)
Hydroconductivity (ft/day)							-0.06578
							(0.0145)***
Hydroconductivity* neighbors' pumping, 1 mi							-0.00000
							(0.0000)
Constant	2.93436	2.75866	2.53294	2.56919	2.52101	2.24895	3.79175
	(0.5430)***	(0.5441)***	(0.5457)***	(0.5459)***	(0.5467)***	(0.5492)***	(0.5820)***
R^2	0.00474	0.00504	0.00543	0.00531	0.00533	0.00576	0.00560

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. Standard errors in parentheses. N is 648554. All measures of amount pumped are in acre-feet. Neighbors' pumping is exclusive of inner radius, i.e., "Neighbors' pumping, 4 mile" is exclusive of pumping within a radius of 3 miles.

Table 5: Instrumental Variables Regressions of Acre-feet Pumped

	(1) 0.5-mile	(2) 1-mile	(3) 2-mile	(4) 3-mile	(5) 4-mile
Pumping at other wells owned by i's owner (AF)	-3.04e-06***	6.72e-06***	1.39e-05***	2.81e-05***	5.67e-05***
	(5.38e-07)	(1.08e-06)	(2.16e-06)	(4.33e-06)	(8.68e-06)
Neighbors' pumping (AF)	0.000154***	0.000252***	8.63e-05***	4.90e-05***	3.09e-05***
	(5.49e-05)	(2.38e-05)	(1.07e-05)	(6.33e-06)	(4.27e-06)
Acres planted on irrigable land	0.768***	0.766***	0.765***	0.764***	0.764***
	(0.00521)	(0.00521)	(0.00522)	(0.00522)	(0.00523)
Appropriation contract	0.111***	0.110***	0.109***	0.109***	0.109***
	(0.00261)	(0.00261)	(0.00261)	(0.00261)	(0.00261)
Precipitation (in)	-3.748***	-3.726***	-3.716***	-3.709***	-3.707***
	(0.0813)	(0.0813)	(0.0814)	(0.0814)	(0.0815)
Potential recharge (in)	4.379***	4.459***	4.467***	4.480***	4.486***
	(0.358)	(0.358)	(0.358)	(0.358)	(0.358)
Mean slope (%)	-1.287***	-1.310***	-1.337***	-1.326***	-1.325***
	(0.397)	(0.397)	(0.397)	(0.397)	(0.397)
Irrigated capability class (dummy)	-5.021***	-5.078***	-5.058***	-5.018***	-5.020***
	(0.810)	(0.809)	(0.810)	(0.810)	(0.810)
Available water capacity (cm/cm)	-432.7***	-436.0***	-438.5***	-440.1***	-439.6***
	(12.16)	(12.15)	(12.17)	(12.19)	(12.19)
Constant	178.8***	178.5***	178.6***	178.6***	178.4***
	(2.965)	(2.963)	(2.964)	(2.964)	(2.964)
R^2	0.521	0.522	0.522	0.522	0.522
Test of excluded IVs: Prob>F	0.0000	0.0000	0.0000	0.0000	0.0000
Average neighbor effect	**0.012**	**0.013**	**0.002**	**0.001**	**0.001**
Average own effect	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. N=58531. Neighbors' pumping is a weighted sum, absolute value of the weights, exclusive of pumping in the smaller radius, i.e., 4 mile radius is exclusive of pumping in 3 mile radius. All pumping amounts are in acre-feet. Standard errors in parentheses. Average effect is beta on neighbors' pumping times the average weight.

Table 6: First Stage Relationship Between Neighbors' Pumping and Neighbors' Permit Amounts

	Acre-feet pumped	Acre-feet pumped
Permit amount (acre-feet)	0.328***	0.363***
	(0.002)	(0.002)
Precipitation (in)	-3.153***	
	(0.075)	
Slope (%)	-6.144***	
	(0.463)	
Irrigated capability class=1	-7.387***	
	(0.950)	
Water capacity (cm/cm)	-606.9***	
	(14.123)	
Constant	259.678***	60.87***
	(3.402)	(0.704)
N	58567	60150
F-statistic for instrument	18432.7	27101.6
R^2	0.34	0.31

Note: * p<0.05, ** p<0.01, *** p<0.001. Standard errors in parentheses.